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A Novel NIRS Index to Evaluate Brain Activity in Prefrontal Regions While Listening to First and Second Languages for Long Time Periods

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***Abstract*—**Near-infrared spectroscopy (NIRS) has been widely used as a non-invasive method to measure brain activity, but it is corrupted by baseline drift noise. Here we present a method to measure regional cerebral blood flow as a derivative of NIRS output. We investigate whether, when listening to languages, blood flow can reasonably localize and represent regional brain activity or not. The prefrontal blood flow distribution pattern when advanced second-language listeners listened to a second language (L2) was most similar to that when listening to their first language (L1) among the patterns of mean and standard deviation. In experiments with 25 healthy subjects, the maximum blood flow was localized to the left BA46 of advanced listeners. The blood flow presented is robust to baseline drift and stably localizes regional brain activity.

***Keywords*—**NIRS, oxy-hemoglobin, baseline drift, blood flow, working memory, BA46, first language, second language.

I. INTRODUCTION

BRAIN activity when processing languages has been investigated by both scientists and engineers in the fields of cognitive science, neurobiological mechanisms, psychology, linguistics, and information technology, and has been investigated in terms of working memory. Basic studies have developed functional models of working memory [2] and revised as a 2000 model [3]–[5]. Many researchers now use the 2000 model [5] to investigate brain activity during language processing. The model has the structure of a "central executive" which functions as an operating system and controls three types of short-term memory: the "episodic buffer", the "visuospatial sketchpad", and the "phonological loop". Among these types of memory, the phonological loop plays a prominent role in language processing [27], [28]. Regarding the limitation of working memory capacity, Miller presented a mental storage capacity which is considered to be the magical number 7 2 [25]. Cowan proposed that this magical number is 4 in short-term memory in reconsideration in the brain [7]. The memory holding time of the short-term memory in the phonological loop is limited and Baddeley reported that the time of voice sound is a few seconds [5], [6] and Jackendoff reported that it is 3 s [13]. Thus the period of language processing is considered to be around 2–3 s. fMRI images showed that the working memory is localized in the left brain and the cognitive system is realized by cooperating with the language area in a part of the frontal lobe [20], [29], [30]. These studies showed that when subjects listen to short phrases, regions in comparison with the control—the anterior cingulate cortex, the left inferior frontal gyrus, the visual association cortex and the superior parietal lobule—are activated simultaneously. Thus the regions should be the base for the function of working memory. The regions of the "central executive" function are mainly distributed in the middle prefrontal gyri BA 46/10, BA 9/44 and BA 45 in the Brodmann area [30].

Various measuring instruments have been used to clarify brain activity. Such instruments include magnetic resonance imaging (fMRI), magnetoencephalography (MEG), positron emission tomography (PET), electroencephalogram (EEG), and near-infrared spectroscopy (NIRS). These instruments have different characteristics. fMRI and PET have high spatial resolution, but they must be set up and used in a special environment such as a magnetic shielded room. Furthermore, they are invasive and should be restricted to subjects who have undergone precise medical inspections or research under special conditions. In contrast to these instruments, although EEG and NIRS have low spatial resolution, they are noninvasive, less restrictive and can be used in normal spaces such as at home. Among them, EEG is sensitive to artifacts by myoelectricity due to body movement. NIRS measures oxy-hemoglobin (oxy-Hb) as the regional cerebral blood volume is insensitive to myoelectricity and robust to artifacts so it can be used as a wearable device.

Depending on the characteristics of the instruments noted above, fMRI has been used to localize regions of brain activity in detail, for example in studies of honorification judgment in Japanese [26], agrammatic comprehension [17], language comprehension vs. language production [21], the functional organization of language in the adult brain [23], [24] and the functional connectivity between brain regions involved in learning words of a new language [40] using detailed brain imaging. PET was used for precise localization of syntactic

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comprehension regions [38].

The event related potentials (ERP) from EEG were also used based on their characteristics of responding to sudden stimuli. Studies to assess the effect of additional tasks on language perception in L2 [12], effects of grammatical categories [42], neural mechanisms of word order processing [43], age-related and individual differences during language comprehension [9] and the masked onset priming effect [39] were conducted by ERP using EEG. The EEG signal provides additional steady-state visual evoked potentials (SSVEP) which were mainly used as a Brain Computer Interface (BCI) signal [1], [14], [41], [45].

The non-invasive and less-restrictive characteristics of NIRS and fNIRS make these approaches suitable for measuring subjects of all generations, from newborns to the elderly. Thus, the age effects of language associated brain activity have been investigated by many researchers, such as discourse comprehension [35], semantic processing of words [15], neuro-functional (re)organization underlying narrative discourse processing [36], verbal fluency [16], language acquisition in infancy [33], language imaging studies in human newborns and adults [32], presurgical assessment of language function in children [11], bilingual babies' phonetic processing advantage [31] and brain activity by bilinguals [36]. Recently, wireless recording systems of EEG-NIRS have been developed [34], enabling these systems to be taken outside the laboratory [10] and used for various investigations and applications in a variety of environments.

NIRS includes an inherent problem caused by the uncertainty of the optical path length of near-infrared light [18], [19], [22], [44]. The technique does not yield an absolute measurement of hemoglobin concentration as regional cerebral blood volume but a relative measurement from a baseline. The baseline as a reference is determined by measuring the brain at rest. Placing subjects in the resting state does not necessarily stop them from thinking and producing brain activity; they may consider something which yields slow changes in hemoglobin concentration, causing baseline drift. There are several strategies for lowering brain activity in the resting state, such as making the subject listen to white noise [37]. If the rest interval and the task interval are set to be constant and the same tasks are given sequentially, then averaging the NIRS data over each rest-task interval reduces the baseline drift noise. Furthermore, if the rest-task interval is shorter than the period of baseline drift, the NIRS output is less corrupted by noise. However, for the long period of a continuous task such as language listening, it is difficult to avoid baseline drift.

The limitations and problems of fNIRS for assessing speech related tasks are thoroughly described in the literature [8].

In this paper, we present a new variable from NIRS: regional cerebral blood volumetric flow (blood flow) with the dimension [m・(mol/s)/l・mm], instead of regional cerebral blood volume with the dimension [m・(mol)/l・mm]. In terms of signal processing, blood flow is a high-pass-filtered variable of oxy-Hb, and the low-frequency component is suppressed whereas the high-frequency component is enhanced. Thus, the blood flow suppresses low-frequency drift and also suppresses some slow-changing brain activity and enhances the quick-changing activity associated with language processing.

This paper investigates whether or not blood flow can represent brain activity when listening to languages, especially when listening to long sentences. If it can, then blood flow measured by compactly-designed NIRS topography could be effectively used for various applications including language learning BCI systems.

II. METHODS

A. Definition of Blood Flow

Variables and symbols are defined as follows:

t [s] : time
T [s] : time interval between tasks
n : total number of NIRS channels
i : NIRS channel (i = 1, 2, ・・・, n)
i* : channel on the most activated brain region
$\boldsymbol{h}(t) = [h_1(t), h_2(t) \cdots h_i(t) \cdots h_n(t)]^T$ [m・(mol)/l・mm]: oxy-Hb or blood volume of all channels during $0 \leq t \leq T$
$\boldsymbol{f}(t) = [f_1(t), f_2(t) \cdots f_i(t) \cdots f_n(t)]^T$ [m・(mol/s)/l・mm]: blood flow of all channels during $0 \leq t \leq T$

The blood flow $f_i(t)$ is defined as follows:

$$f_i(t) = \frac{dh_i(t)}{dt} \tag{1}$$

A : Advanced, N: Novice
J : code of the parameters cited in this paper
j = 1 : mean of $h_i(t)$ with respect to time
j = 2 : standard deviation of $h_i(t)$ with respect to time
j = 3 : root mean square of $f_i(t)$ with respect to time
j* : code of parameter which represents brain activity when listening to long L2 sentences
k : code of tasks when listening to L1 and L2 by different groups
k = 1 : listening to L1 by subjects
k = 2 : listening to L2 by the subjects in group A
k = 3 : listening to L2 by the subjects in group N

Furthermore, parameters and correlation coefficients are defined as:

$I_{i,j,k}$ [m・(mol)/l・mm] or [m・(mol/s)/l・mm]: parameter j under task k at channel i
$\boldsymbol{I}_{j,k} = [I_{1,j,k} I_{2,j,k} \cdots I_{n,j,k}]^T$: distribution pattern of parameter j under task k
$X\{\boldsymbol{I}_{j,1}, \boldsymbol{I}_{j,k}\}$: correlation coefficient of distribution patterns $\boldsymbol{I}_{j,1}$ vs. $\boldsymbol{I}_{j,k}$

B. Scheme Used to Investigate the Effectiveness of Blood Flow

Fig. 1 shows the scheme used to investigate whether or not blood flow can represent brain activity when listening to languages.

As shown at the bottom of Fig. 1, first we let subjects listen to the languages in tasks k = 1, 2, and 3. Oxy-Hb $h_i(t)$ in all channels i = 1,2,3, ・・・, n were measured in the L1 and L2 listening tasks using multi-channel NIRS topography, then the patterns of the parameters $I_{j,k}$ for j = 1, 2, and 3 were calculated from the NIRS data. These patterns are summarized in the table in the upper left of Fig. 1. From the data patterns, the correlation coefficients $X\{I_{j,1}, I_{j,k}\}$ between the patterns $I_{j,1}$ and $I_{j,k}$ were calculated as shown in the table in the upper right of

Fig. 1.

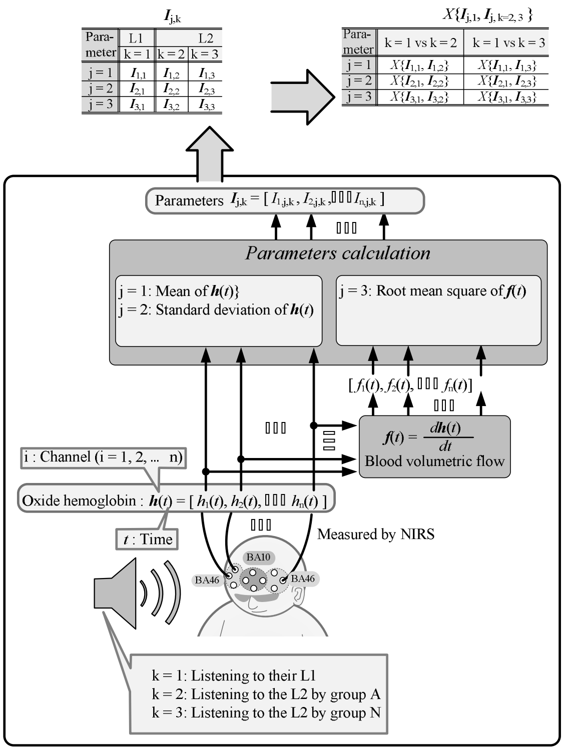


Fig. 1 Experimental scheme to investigate whether or not blood flow can represent brain activity during language processing

If the correlation coefficient of patterns of a parameter is near to one, it indicates that regional brain activity when listening to L2 is similar to that when listening to L1. The parameter with maximum correlation is expressed by j*, which stably represents the brain activity when listening to long sentences. Furthermore, the correlation of parameters expressed by j* for the subjects in group A must be greater than those for the subjects in group N. Mathematically, the parameter j* must satisfy the following two conditions:

$$j^* = j \text{ which maximizes } X\{\boldsymbol{I}_{j,1}, \boldsymbol{I}_{j,2}\} \quad (2)$$

$$X\{\boldsymbol{I}_{j^*,1}, \boldsymbol{I}_{j^*,2}\} > X\{\boldsymbol{I}_{j^*,1}, \boldsymbol{I}_{j^*,3}\} \quad (3)$$

Moreover, previous studies showed that one of the working memory regions used for language processing is located in the middle prefrontal gyri including BA46 [31]. Thus the parameter expressed by j* for the subjects in group A, i.e., k = 2, must be maximum at channel i* which is on BA46. Mathematically, the following condition must be satisfied:

$$\boldsymbol{I}_{i^*,j^*,1} > \boldsymbol{I}_{i,j^*,2} \text{ for all i excluding } i^* \quad (4)$$

Statistical tests by ANOVA and the multiple comparison method were used to judge whether or not the condition in (4) is satisfied.

C. Experiments

All experiments were carried out in accordance with the program checked and approved by the Ethics Committee of the Medical Research Institute of the Tokyo Medical and Dental University (permission No. 2012-15).

Table I shows the basic specifications of the NIRS topography device used in the experiments. The device is wearable and robust to myoelectric artifacts.

TABLE I
BASIC SPECIFICATIONS OF THE NIRS WEARABLE OPTICAL TOPOGRAPHY DEVICE

Device	WOT-100 (Hitachi Co.)
Measurement variables	Hemoglobin concentration (oxy, deoxy, total)
Optical source	705 nm and 830 nm near-infrared light
Sampling interval and moving average smoothing	200-ms sampling interval and 25-point moving average with 0.088 Hz cut-off frequency
Ten channels from 1 to 10 (n = 10)	10 channel probes cover the right and left BA46 and BA10 regions. Probe diameter 11 mm
Size and weight	W: 260 mm, D: 280 mm, H: 92mm, Weight: 700g

Fig. 2 shows the setup of the headset and detection points. All of the detection points are on the forehead, and so there is no disturbance or mis-setting due to hair. The near-infrared light detecting probes arrayed on the upper part and lower part were set around the F7-Fpz-F8 line of the international 10-20 system.

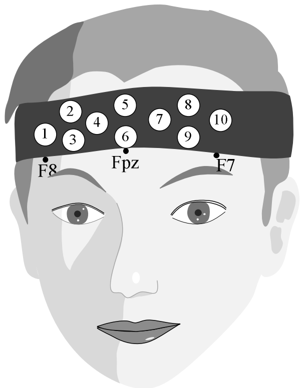


Fig. 2 NIRS setup for the experiments

D. Experimental Protocol

The experimental protocol was as follows: No. 1: resting for 60 s; No. 2: explanation of tasks; No. 3: headset setting; No. 4: mental preparation; No. 5: start of recording; No. 6: baseline calibration for 10 s; No. 7: resting for 10 s; No. 8: start of tasks; No. 9: tasks: (a) listening to L1 and (b) listening to L2; No. 10: end of task; No. 11: end of recording; No. 12: exit survey and oral test. All experiments were conducted according to the above protocol.

E. Subjects and Tasks

The subjects were 25 healthy Japanese university students (7 females and 18 males) aged 20 to 25 in an engineering department whose TOEIC$^{(R)}$ scores ranged from 295 to 915. The 10 subjects with TOEIC$^{(R)}$ scores of over 700 were assigned to group A and the 15 subjects with TOEIC$^{(R)}$ scores of less than 500 to group N. All of them were right-handed, their L1 was Japanese, and they had learned English as an L2 for three years in middle high school, three years in high school and two or three years at university.

The first task was listening to L1. We let the subjects listen to Japanese radio news for 163 s, which was at the speed of 121 Japanese words/minute (wpm). The second task was listening to L2. Depending on the listening skill of the subjects in groups A and N, we let them listen to L2 with different readability levels defined by Flesch-Kincaid Grade (FKG). Table II shows the FKG level, titles of articles, numbers of words, time, and the words/minute and articles assigned to each group. The first article with level of 3.18 was used as a training task before the experiments. The L2 sentences had been read and recorded by native speakers. For some subjects, an L2 article with a certain FKG level may be easily understandable and interesting, but not for other subjects. In such tasks with a difficulty level of L2 or uninteresting content, brain language processing may not be carried out.

TABLE II
ARTICLES USED IN THE EXPERIMENTS

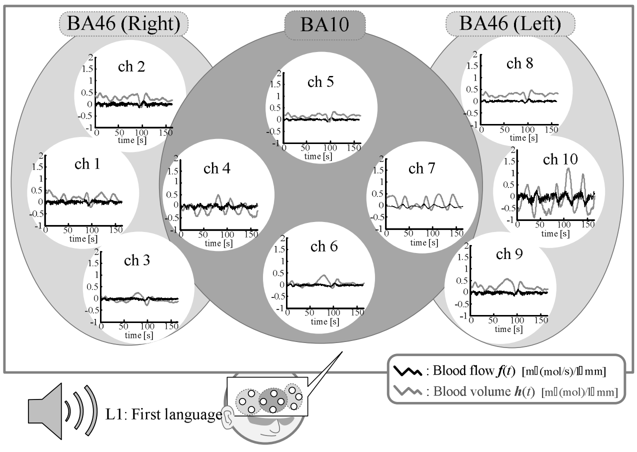
Language	Text level	Title	Words	FKG level	Group
Japanese		2010.08.02 Foot-and-mouth disease-related news (Kagoshima local)	328		A/N
English	0	Let's Talk about Yesterday	95	3.18	Training
	1	At the Library	88	1.74	N
	2	About Tom's Family	84	2.17	N
	3	Seasonal Troubles	181	3.73	N
	4	The Peach Boy	236	4.56	N
	5	The History of Soy Sauce	198	5.53	A/N
	6	Living by Myself	462	6.34	A/N
	7	Brazil	240	7.12	A/N
	8	Yellow Sand	430	8.10	A/N
	9	Art	604	9.27	A/N
	10	Eco-driving	430	10.3	A
	11	Redefining Fatherhood	392	11.8	A
	12	War	459	12.7	A
	13	Japanese Modern Literature	374	15.5	A

To avoid such problems with the articles, we let each subject listen to six or nine sentences with different difficulty as shown in Table II. In the experiment, we selected the sentence from the exit survey that the subject found easiest to understand and conducted an oral test on the contents of the article. The subjects' answers and the results of the oral tests had no contradictions. We also checked the brain activity around BA46 using the NIRS output and selected the relevant article.

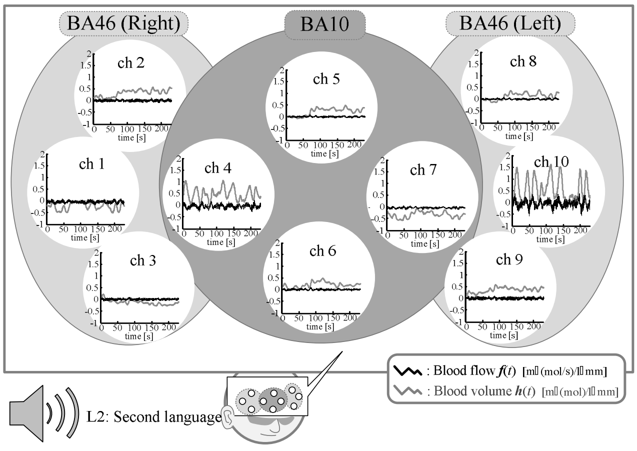
III. RESULTS

A. Ten Channel NIRS Outputs of Blood Volume and Blood Flow

Fig. 3 illustrates the NIRS outputs of blood volume (gray curve) and blood flow $f_i(t)$ (black curve) defined by (1) when (a) listening to L1 and (b) listening to the relevant L2 by a subject with a TOEIC$^{(R)}$ score of 760. The NIRS outputs themselves include slowly changing waves. Some components of the wave might include the oxy-Hb due to the brain activity by listening to languages and might also include the baseline drift. Similar slowly changing waves were observed in the resting period. The blood flow changed around zero and had a mean of zero. Slowly changing low-frequency components were eliminated and the high-frequency components were enhanced.



(a) Listening to their L1



(b) Listening to the L2

Fig. 3 The blood volumes from NIRS (gray curve) with dimension [m・(mol)/l・mm] and the blood flows (black curve) with dimension [m・(mol/s)/l・mm] calculated by (1), when (a) listening to L1 and (b) listening to the relevant L2 by a subject with a TOEIC(R) score of 760.

B. Parameters and Correlation Coefficients

Following the experimental scheme in Fig. 1, we calculated the three parameters when listening to L1 (k = 1) and L2 for the subjects in groups A (k = 2) and N (k = 3). The parameters from the NIRS outputs are the mean (j = 1) and standard deviation (j = 2) of $h(t)$ and the root mean square (j = 3) of $f(t)$. Furthermore, the three (j = 1, 2, 3) 2 (k = 2, 3) correlation coefficients were calculated. These are the correlation coefficients between the parameter patterns when listening to L1 and those when listening to L2 by the two groups for the three parameters. The results are shown in Fig. 4.

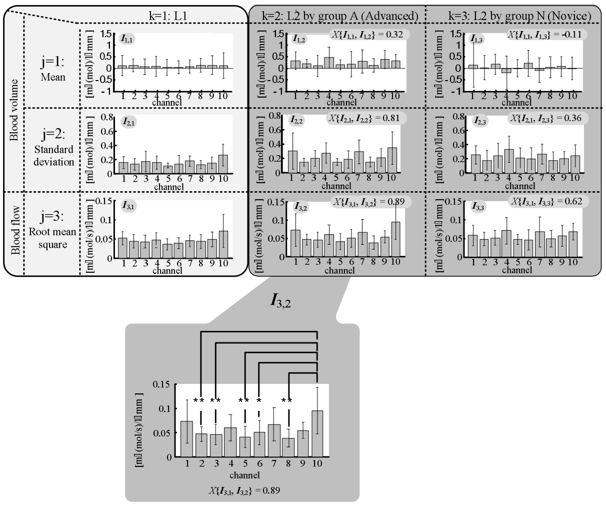


Fig. 4 Average and standard deviation of the parameters: the mean and standard deviation of $h(t)$ and the root mean square of $f(t)$ of each channel in NIRS outputs when listening to L1 and listening to L2 for the subjects in groups A and N and the correlation coefficients between the parameter patterns. The correlation coefficients are shown as numerical values for each parameter in the graphs. Statistically significant difference of the root mean square of blood flow between channel 10 on the left BA46 and other channels

From the results in the upper of Fig. 4, when subjects listened to L1, the root mean square of blood flow and standard deviation were at their maximum at channel 10. Channel 10 is in the upper F7 by the international 10-20 system and is around the left BA46. Among the patterns for the three parameters, the correlation by the root mean square of blood flow between L1 and L2 for the subjects in group A was a maximum of 0.89 among the three parameters; that by the standard deviation was 0.81 and that by the mean was 0.32. Using the notation of (2), these results can be described as follows:

$$j^* = 3 \ \{\text{root mean square of } f_i(t)\ \} \tag{5}$$

Furthermore, from the correlation coefficients in Fig. 4, by using the notation in (3), the correlation coefficients can be described as follows:

$$X\{I_{3,1}, I_{3,2}\} = 0.89 > X\{I_{3,1}, I_{3,3}\} = 0.62 \tag{6}$$

Among the parameters, the parameter j* = 3 {root mean square of $f_i(t)$ } was at its maximum at channel 10 which is the same channel at its maximum when listening to L1. Note in Fig. 4, j = 3; the root mean square of blood flow for the subjects in group N was a maximum at channel 4 which is around BA10. All three parameters had a maximum value at some channel. We applied ANOVA and the multiple comparison method to the parameters obtained by listening to L2 to test whether they are significantly different from other channels. Only the root mean square of blood flow at channel 10 for the subjects in group A had a significant difference from the other channels; no other parameters had a value with a significant difference from other channels. By using the notation in (4), these results can be described as follows:

$$I_{10,3,2} > I_{i,3,2} \text{ for all i excluding i = 10} \tag{7}$$

The lower of Fig. 4 shows the channels that had a statistically significant difference, namely channel 10 on the left BA46. The graph shows the statistically significant difference between channel 10 and the other channels. Significance levels of 1%, 5% and no significance are expressed by symbols **, * and +, respectively.

IV. DISCUSSION

NIRS outputs themselves include slowly changing waves as illustrated in Fig. 3 in the lengthy task of listening to languages, in which baseline drift is unavoidable. The means of $h(t)$ with respect to time represent the low-frequency components of the wave having the least similarity to the brain regional activities between the case when listening to L1 and when listening to L2 by advanced L2 listeners. The correlation coefficient was a minimum of 0.32 as shown in Fig. 4. However, the standard deviations of $h(t)$ and root mean squares of $f(t)$ had the correlation coefficients 0.81 and 0.89, respectively. These represent the degree of fluctuation or the high-frequency components of the wave and had greater correlation coefficients than those by the means. This result shows that the lengthy task of language listening is strongly influenced by the slow baseline drift. Language listening stimuli are different from stimuli where tasks are given at the beginning once and the brain autonomously processes the tasks without any external information, such as the sequential subtraction of 7 from an initial value of 100 and verbal fluency tasks. Listening to languages involves external sequential stimuli word by word and sentence by sentence. In such stimuli in language processing, the working memory whose central executive is left BA46 [30] functions and the memory holding time of voice sound is a few seconds [5], [6] and the brain might work intermittently. These previous works reasonably correspond to the present results. Among the standard deviations of $h(t)$ and the root mean square of $f(t)$ proposed here, the root mean squares had a maximum around the left BA46 for the subjects in group A with a significant difference from other brain regions. This fact also indicates that the blood flow can reasonably represent the brain activity during language processing. Furthermore, the blood flow waves in Fig. 3 show no drifting with a zero mean, thus yielding stable and robust measurements.

From a pedagogical point of view, English learners with TOEIC$^{(R)}$ scores of over 700 listened to English with a level equal to their L1 and those with scores of less than 500 did not consider the contents of the English.

V.CONCLUSIONS

Conventional studies on brain activity by neuroimaging using NIRS have focused on what brain regions are activated by language stimuli. The outputs of NIRS, i.e., oxy-hemoglobin concentration with dimension of [m · (mol)/l · mm] or its temporal moving average, have been used as indicators of such activity. However, in the case of lengthy tasks, NIRS measurements are corrupted by inherent baseline drift noise. In this paper we proposed the time derivative of the oxy-Hb concentration with dimension [m · (mol/s)/l · mm] as an indicator of the blood flow which includes less baseline drift. Our objective was to investigate whether or not blood flow can effectively represent brain activity when listening to one's native language and a second language.

We tested 25 healthy subjects whose L1 was Japanese and L2 was English. Ten subjects (group A) had TOEIC$^{(R)}$ scores of over 700 and 15 (group N) had scores of less than 500. The subjects in group A accessed L2 like L1 when L2 was of a relevant level. We measured 10-channel NIRS data around the prefrontal regions of the subjects when they listened to L1 (radio news) and L2 with different readability levels. We calculated the root mean square of blood flow, and for comparison we calculated the mean and standard deviation of the oxy-Hb concentration itself. In order to show that the blood flow is effective, we used the criterion that the regional brain activity pattern given by the root mean square of blood flow when subjects listened to L1 and the pattern when the subjects in group A listened to L2 must have the maximum correlation among the three parameters. In the experiments, the L2 articles were those that most stimulated the brain activity of the subjects. Furthermore, in order to investigate the locations of activated local brain regions, as well as to investigate whether the blood flow at the localized region was a maximum with a statistically significant difference from other regions, we applied ANOVA and the multiple comparison method to the 10 channel parameter patterns.

Among the patterns by the three parameters, the correlation coefficient by the root mean square of blood flow between L1 and L2 for the subjects in group A was a maximum of 0.89. The correlation by the standard deviation was 0.81 and that by the mean was 0.32, which was the least among the three parameters. When listening to L1, the root mean square of blood flow and the standard deviation were maximum at channel 10 which is in the upper F7 by the international 10-20 system and is around the left BA46. When listening to L2 by group A, the root mean square of the blood flow was a maximum at channel 10 which is the same region when listening to L1. When listening to L2 by group N, the root mean square of blood flow was a maximum at channel 4 which is around BA10. The results by ANOVA and the multiple comparison method showed only that the root mean square of blood flow for the subjects in group A had a channel with a value statistically significantly different from the other channels. In group A, it was channel 10 which is on the left BA46.

Thus, parameters representing the temporal changes in NIRS such as the blood flow and standard deviation can effectively represent brain activity rather than the conventionally-used mean value which shows low-frequency characteristics. The blood flow can reasonably represent the brain activity when listening to L2. It is a stable and robust parameter to drift noise and shows the localized activated brain region with a significant difference from other brain regions.

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